

# OH MASERS IN G11.904–0.141

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## ABSTRACT

The massive star-forming region G11.904–0.141 is one of only 11 sources to show maser emission in the highly-excited 13441 MHz transition of OH. VLBA observations of the 1665, 1667, 4765, and 13441 MHz transitions of OH toward G11.904–0.141 are presented. Masers are detected at 1665, 1667, and 4765 MHz, but the 13441 MHz masers are not detected. Consistent magnetic field strengths of approximately +3.5 mG are detected in the ground-state masers, in contrast with a possible –3.0 mG magnetic field previously detected at 13441 MHz. The variable 13441 MHz masers may be associated with an outflow.

*Subject headings:* masers — ISM: individual (G11.904–0.141) — stars: formation — radio lines: ISM — ISM: molecules

## 1. INTRODUCTION

Massive star-forming regions in the Galaxy are commonly seen to host OH maser emission, including masers from excited states. However, maser emission in the highly-excited 13441 MHz transition is rare. To date, only 11 sources are known to host 13441 MHz masers, most detected only recently (Turner et al. 1970; Baudry & Desmurs 2002; Caswell 2004). In addition, several possible sources were detected by Balister et al. (1976) but not subsequently redetected.

Nearly all 13441 MHz maser sources display nearly equal fluxes in the left (LCP) and right circular polarized (RCP) modes. Conventional wisdom attributes this to the small Zeeman splitting coefficient ( $0.018 \text{ km s}^{-1} \text{ mG}^{-1}$ ). Since a typical magnetic field of a few milligauss does not split the LCP and RCP lines of a Zeeman pair by a full linewidth, velocity-coherent amplification of the LCP and RCP lines should be similar, giving a flux ratio of nearly unity. Approximately equal LCP and RCP fluxes are observed in 10 of 11 13441 MHz OH maser sources, including for individual Zeeman pairs observed at very long baseline interferometric (VLBI) resolution in W3(OH) (Baudry & Diamond 1998). The one exception is G11.904–0.141 (hereafter G11.90), for which the RCP/LCP flux ratio was 3.4 in the Caswell (2004) observations and larger in the Baudry & Desmurs (2002) observations, in which the LCP feature was not detected. Caswell (2004) infers a possible magnetic field of –3.0 mG, which produces a negligible splitting compared to the line width ( $0.24 \text{ km s}^{-1}$  RCP and  $0.31 \text{ km s}^{-1}$  LCP) and therefore would be expected to result in fairly equal RCP and LCP fluxes.

Observations of multiple OH maser transitions at VLBI resolution would also provide information on whether the several maser transitions are co-spatial, with implications for 13441 MHz maser modelling. Multitransition maser overlaps provide strong observational constraints to test maser models and to derive local physical conditions. The literature includes only one source, W3(OH), observed at 13441 MHz at VLBI resolution (Baudry & Diamond 1998). Further observations are needed in order to understand the conditions that produce these rare masers.

It is for these reasons that G11.90 was selected for study at higher spatial resolution. Results are reported in this Letter.

## 2. OBSERVATIONS

Four transitions of OH masers were observed with the Very Long Baseline Array (VLBA) in three different epochs (experiment code BF088). The ground-state 1665.40184 and 1667.35903 MHz masers were observed simultaneously on 2006 Feb 22 and the 4765.562 MHz masers on 2006 Feb 27. Total observing time was 6.5 hr per run, with approximately 3 hr spent on G11.90. The 13441.4173 MHz masers were observed with both the VLBA and the Green Bank Telescope (GBT) on 2006 Aug 29 over a total of 4.5 hr, with approximately 2 hr spent on G11.90. Most of the remaining time was used to observe the nearby calibrator J1825–1718 for phase calibration. The calibrator 3C286 was observed as a fringe-finder and polarization calibrator.

The 1665, 1667, and 4765 MHz masers were observed in full polarization mode using 0.125 MHz bandwidths divided into 128 spectral channels for a spectral resolution of  $0.18 \text{ km s}^{-1}$  at 1665/1667 MHz and  $0.06 \text{ km s}^{-1}$  at 4765 MHz. The 13441 MHz masers were observed in dual circular polarization mode using a 1.0 MHz bandwidth divided into 512 spectral channels for a spectral resolution of  $0.04 \text{ km s}^{-1}$ .

Because G11.90 is significantly scatter-broadened at long wavelengths, no signal was detectable on the longer baselines at 1.6 GHz. The usable array at 1.6 GHz effectively consisted of the inner five antennas plus a small amount of data from North Liberty, IA. Blank sky noise in the LCP and RCP image cubes was  $18 \text{ mJy beam}^{-1}$  in a single channel with a synthesized beam size of  $67 \times 32 \text{ mas}$ . At 4.7 GHz, sufficient signal was seen to determine adequate calibration on baselines to all antennas except Mauna Kea, HI and St. Croix, VI. Blank sky noise in Stokes I was  $8 \text{ mJy beam}^{-1}$  in a  $9 \times 3 \text{ mas}$  synthesized beam. At 13441 GHz all 10 VLBA antennas and the GBT produced usable data, for a blank sky Stokes I noise level of  $3 \text{ mJy beam}^{-1}$  in a  $2.8 \times 0.7 \text{ mas beam}$  when averaged over 5 spectral channels, comparable to a maser line width.

All data were phase-referenced to J1825–1718 ( $3^\circ 5'$  away from G11.90) using a cycle time of 5 min at 1665/1667 MHz and 3 min at 4765 and 13441 MHz. The phase-referenced 1665 and 1667 MHz image quality was poor, but the reference feature (1665 MHz LCP) was sufficiently bright to determine a position. The reference maser was then used to self-calibrate the 1665 and 1667 MHz LCP and RCP data for further imaging. Phase-referencing at 4765 MHz produced excellent image quality. Random errors from centroid fitting in determining reference feature positions are less than 1 mas at 1665

and 4765 MHz. However, systematic errors can dominate at 1.6 GHz, with ionospheric fluctuations able to introduce apparent shifts on the order of 20 mas as well as ambiguities of which peak corresponds to the actual source for nodding calibration under poor ionospheric conditions (Chatterjee 1999). Much of the power in the phase-referenced 1665 MHz map was distributed among sidelobes, but there was a clear brightest feature, with the next-brightest sidelobes distributed symmetrically about this feature. It therefore appears that the ionosphere was sufficiently stable during observations to permit phase-referencing to successfully determine the position of the 1665 MHz LCP feature, with likely errors no more than a few milliarcseconds.

### 3. RESULTS

Detected masers are detailed in Table 1. Flux densities are given for the peak channel of emission for each spot in the natural polarization mode: LCP and RCP for the 1665 and 1667 MHz transitions (for which the Zeeman splitting coefficient is large) and Stokes I for the 4765 MHz transition (in which the Zeeman splitting coefficient is a factor of  $\sim 1000$  smaller). No masers were detected at 13441 MHz.

It is possible that several maser spots are spatially blended together in the ground state. At a distance of 5.1 kpc (Caswell & Vaile 1995), the synthesized beam size corresponds to a spatial size of over 200 AU, which is larger than the typical OH maser clustering scale (Fish & Reid 2006). The ground-state masers are significantly broadened, although not atypically so for sources at low Galactic longitude (e.g., Szymczak 1985; Fish & Reid 2006), while the 4765 MHz masers appear to be much smaller, consistent with interstellar scattering varying as  $\nu^{-2}$  or  $\nu^{-2.2}$  (e.g., Cordes et al. 1984).

Emission at 1665 and 1667 MHz is coincident to a small fraction of the beam size. Where 1665 and 1667 MHz masers overlap, magnetic field strengths and systemic velocities (corrected for the Zeeman effect) are in excellent agreement. Masers in the 4765 MHz transition are offset slightly to the southeast from the ground-state masers though at approximately the same LSR velocity as ground-state masers when the latter are corrected for Zeeman splitting. All OH masers fall in the velocity range spanned by 6668 and 12178 MHz methanol masers (Menten 1991; Caswell et al. 1995a,b; Szymczak et al. 2000). The total spatial extent of the 1665, 1667, and 4765 MHz masers is less than 100 mas (500 AU) in each of the right ascension and declination directions. Maser emission in the 6035 MHz transition spans 130 mas, mostly in the declination direction (Caswell 1997). The positions of the northern and southern 6035 MHz masers are consistent with being approximately coincident with the line of ground-state masers and 4765 MHz maser group, respectively, given the positional uncertainty of the Caswell (1997) Australia Telescope Compact Array (ATCA) observations.

All masers brighter than 1 Jy are seen in linear polarization as well, typically at the 10% level. The weaker 4765 MHz spot appears to have a large linear polarization fraction but may suffer from contamination from the nearby brighter spot. The polarization position angles are likely affected by large Faraday rotation between the source and the observer, since the highly-broadened maser sizes at 1.6 GHz imply a large electron density along the propagation path. Typical dispersion measures in the general direction and near the distance of G11.90 are 250–500  $\text{cm}^{-3}$  pc (from the ATNF Pulsar Cata-

logue, Manchester et al. 2005). Assuming an average line-of-sight Galactic magnetic field of 2  $\mu\text{G}$  (e.g., Heiles 1976), expected rotation measures imply a Faraday rotation of greater than 1 rad at 4765 MHz and tens of radians at 1.6 GHz.

No emission is detected at 13441 MHz, to a  $5\sigma$  limit of 20  $\text{mJy beam}^{-1}$  in each of LCP and RCP when the spectral resolution is degraded to 0.22  $\text{km s}^{-1}$ , comparable to the maser line width in the Caswell (2004) detection. RCP emission was detected at the 200  $\text{mJy}$  level in 1999 May by Baudry & Desmurs (2002), while LCP emission was not detected at all. RCP and LCP flux densities were measured to be 240  $\text{mJy}$  and 70  $\text{mJy}$ , respectively, by Caswell (2004) in 2003 June. The 13441 MHz masers in G11.90 are clearly variable. Despite the small number of known 13441 MHz maser sources and the relative paucity of observations thereof compared to less-excited states, 13441 MHz masers are known to display large variability in general (see the discussion in Caswell 2004). Variability has been noted in other maser transitions in G11.90 as well, including OH 6035 MHz (Caswell & Vaile 1995) and methanol 6668 MHz (Szymczak et al. 2000). In the other transitions reported herein, the 1665 MHz masers have become moderately stronger and the 1667 MHz masers moderately weaker since the Caswell & Haynes (1983) epoch (1980–1981), while the 4765 MHz maser parameters (peak velocity, flux density, and position) are all in excellent agreement with the ATCA observations of Dodson & Ellingsen (2002, epoch 2000 September 15–16). A monitoring study of the 4765 MHz masers show no significant variability over nearly two years (Smits 2003).

Magnetic fields of about +3.5 mG are detected in the ground-state transitions, where the positive sign represents a magnetic field whose line-of-sight component is oriented away from the observer. LCP and RCP velocities were determined by taking the central velocity of peak emission; corresponding magnetic field strength errors are 0.2 mG at 1665 MHz and 0.4 mG at 1667 MHz. These results are consistent with the Parkes spectra of Caswell & Haynes (1983), which show RCP emission redshifted with respect to stronger LCP emission at both 1665 and 1667 MHz. However, the positive magnetic field values contrast with observations in the excited states. Caswell & Vaile (1995) detected no Zeeman splitting at 6035 MHz, placing an upper limit of  $|B| < 0.5$  mG. At 13441 MHz, Caswell (2004) detected a marginal magnetic field of  $-3.0$  mG, of similar strength to the detections reported herein but opposite in sign. The 13441 MHz splitting may also be consistent with a zero magnetic field, as indicated by 6035 MHz Zeeman splitting, but is not consistent with the +3.5 mG magnetic fields obtained in the ground-state transitions. It is possible that there is a magnetic field direction reversal across the source, but the VLBA nondetection of the 13441 MHz masers precludes definitive conclusions regarding their location relative to the ground-state masers.

### 4. DISCUSSION

All masers are located near continuum source A in Forster & Caswell (2000). At 8.2 and 9.2 GHz, the continuum emission appears to have two peaks, with the brighter, more compact peak, G11.904–0.142, located nearest the OH emission, to the northeast of the weaker, more extended peak (Forster & Caswell 2000). Extended emission oriented northeast-southwest connects the two peaks, with larger-scale weaker emission elongated north-south. The 1665 and 1667 MHz masers are distributed as 3 distinct sites of emission along a line oriented at a position angle of  $55^\circ$  (east of

TABLE 1  
DETECTED MASERS IN G11.90

Freq. (MHz)	Pol.	RA <sup>a</sup> (J2000)	Decl. <sup>a</sup> (J2000)	$v_{\text{LSR}}^a$ (km s <sup>-1</sup> )	$S^a$ (Jy)	$N_{\text{chan}}^b$	$m_L^c$ (%)	$\chi^c$ (°)	$B$ (mG)
1665	LCP	18 12 11.4314	-18 41 28.827	40.22	1.33	3	8	-11	3.6
1665	RCP	18 12 11.4319	-18 41 28.827	42.33	0.22	1	...	...	...
1665	LCP	18 12 11.4338	-18 41 28.803 <sup>d</sup>	40.75	9.28	5	10	-43	3.6
1665	RCP	18 12 11.4333	-18 41 28.807	42.85	0.84	2	...	...	...
1665	LCP	18 12 11.4352	-18 41 28.793	41.62	0.44	3	...	...	...
1667	LCP	18 12 11.4316	-18 41 28.827	40.76	0.22	1	...	...	...
1667	LCP	18 12 11.4334	-18 41 28.810	41.11	1.00	3	13	0	3.5
1667	RCP	18 12 11.4332	-18 41 28.809	42.34	0.41	2	...	...	...
4765	I	18 12 11.4368	-18 41 28.883	41.86	0.45	3	25 <sup>e</sup>	70	...
4765	I	18 12 11.4371	-18 41 28.881	41.92	1.09	5	5	88	...

<sup>a</sup> Position, central velocity, and flux density of channel of peak emission. <sup>b</sup> Number of channels in which feature is detected. <sup>c</sup> Linear polarization fraction and (electric vector) polarization angle east of north. <sup>d</sup> Reference feature for ground-state masers. <sup>e</sup> Some contamination from nearby brighter feature.

north), with velocities increasing toward the northeast. The absolute position of the brightest peak is located approximately 880 mas to the northwest from the location given in Forster & Caswell (1999), which is reasonably consistent to within the errors that the authors quote.

The maser distribution and velocities hint at a possible outflow origin. Assuming that the 13441 MHz masers, when they are detectable, exist near the other masers, they too may be associated with the putative outflow. If the negative magnetic field marginally detected at 13441 MHz can be believed (Caswell 2004), it is possible that the magnetic field wraps around the outflow, with the 13441 MHz masers spatially offset from the ground-state masers. Should the 13441 MHz masers reappear and become sufficiently bright, further interferometric study would be useful to test this hypothesis. Linear polarization measurements of the 13441 MHz masers would also allow the direction of the magnetic field in the plane of the sky to be inferred.

If an outflow does exist in G11.90, it may be partially responsible for powering the 13441 MHz masers. In other sources, the association of some masers with outflows is clearest in methanol (Zapata et al. 2006) but is seen in other tracers as well, including OH (e.g. De Buizer 2006). OH transitions in star-forming regions are inverted via a complex system of radiative and collisional pumping routes whose relative importance is likely dependent on physical conditions in

the maser region (Gray 2007). Pumping of the 13441 MHz transition is not well understood but probably requires quite energetic conditions, given the rarity of 13441 MHz masers as well as the large excitation of the  $^2\Pi_{3/2}, J = 7/2$  state (290 K above ground). Indeed, in W3(OH), the only source in which 13441 MHz masers have been detected at VLBI resolution, the 13441 MHz masers are located in a region of high excitation where the methanol maser kinematics suggest the existence of an expanding bipolar cone (Baudry et al. 1993; Baudry & Diamond 1998; Moscadelli et al. 2002). Association of 13441 MHz masers with energetic outflows may also naturally explain the high variability usually seen in this transition (Caswell 2004). Further high-resolution studies of 13441 MHz masers, as well as contextualizing high-resolution information from molecular tracers and infrared emission, are required to understand their excitation and their relation to their surroundings.

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*Facilities: VLBA, GBT*

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